

## Invited review

## Zoogeomorphology in the Anthropocene

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## ABSTRACT

The Anthropocene embodies the concept of human impacts on the natural environment, but disagreements exist as to when to identify its inception/starting date. In this paper I illustrate that regardless of the proposed starting date of the Anthropocene, important zoogeomorphic impacts were initiated at each of these proposed starting dates. Humans have profoundly altered geomorphic pathways through extinctions and the near-extirpation of native populations of animal species that strongly influenced hydrology and removal of surface sediment and through the introduction of populations of animals that bring to bear a suite of different geomorphic effects on environmental systems. Domestication of animals brought its own suite of zoogeomorphic implications. Introductions of exotic species, and the spread of feral species, often led to dramatic new geomorphic landscapes because of the absence of natural controls on population expansion. In the mountains of the western USA and elsewhere, the geomorphic actions of animals are being impacted by human-induced climate change. Climate change in some cases affects the spatial pattern and range of species, whereas in other cases it may lead to the extirpation of species with zoogeomorphic impacts.

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## 1. Introduction

Humans have profoundly altered geomorphic pathways during the Anthropocene through their interactions with and impacts upon animal

populations around the world. These interactions include domestication of numerous species, extirpation or near-extirpation of geomorphically significant species, introduction of exotic species into landscapes where those species have no natural enemies, rewilding/reintroduction of species in locations where local or regional extirpation of species had occurred (allowing domesticated species to become feral and widespread

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across landscapes), and alteration of species ranges because of the effects of human-induced climate and land use changes. Each of these forms of interactions induced local to regionally widespread alterations of geomorphic processes, landform creation, and sediment pathways. This paper describes these interactions and alterations within the context of definitions and time periods of the Anthropocene and illustrates that regardless of what temporal parameters are associated with the Anthropocene, zoogeomorphic impacts have occurred across the late Pleistocene and Holocene at every proposed starting point.

## 2. Definitions

**Zoogeomorphology**, the study of animals as geomorphic agents (Butler, 1992, 1995), is a subdivision within the broader realm of biogeomorphology. A variety of geomorphic actions undertaken by animal species have distinct surficial and subsurface impacts and result in sediment movement, landform creation, hydrological and pedological changes, and altered landscapes (Butler, 1995, and references therein; also see Fig. 1, modified from Butler, 2006). The spatial distribution and strength of these actions do not remain constant across time, however, and during the past 10,000–14,000 years human activities have strongly influenced and altered these patterns and strengths.

The term *Anthropocene* was introduced in the year 2000 (Crutzen and Stoermer, 2000; Smith and Zeder, 2013) as a concept indicating that human modification of the environment had reached such a widespread and significant level that a geological epoch distinct from the Holocene had been initiated. Although increasingly embraced by physical and social scientists, as reflected in the recent establishment of professional journals (*Anthropocene*: founded 2013; *The Anthropocene Review*: founded 2014), no universally accepted starting point for the onset of

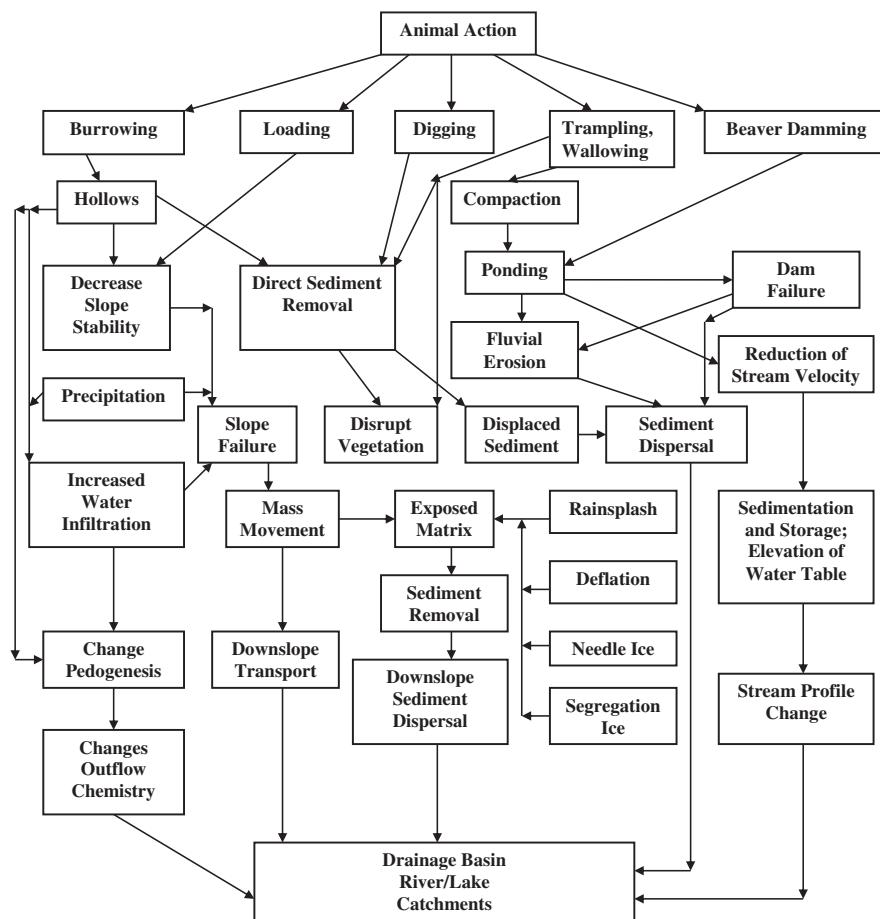
the Anthropocene exists (Smith and Zeder, 2013). Although the Working Group on the Anthropocene (Zalasiewicz et al., 2017) recently recommended formalization of the Anthropocene with an Epoch rank based on a mid-twentieth century boundary associated with radionuclide fallout as a stratigraphic *Golden Spike*, this recommendation has yet to be acted upon and is far from universally accepted as of the writing of this paper.

Recommended starting dates for the Anthropocene span the entirety of the Holocene and even extend back into the last of the Pleistocene. An additional novel suggestion by Smith and Zeder (2013) was to make the Anthropocene coeval with the Holocene, thus avoiding the controversy as to the question (when did the Holocene end and the Anthropocene begin?) That approach also avoids the necessity for a stratigraphic *Golden Spike* required by the International Commission on Stratigraphy for formal recognition of a geologic boundary separating the Holocene from the Anthropocene.

In this paper, I do not take a position on which starting date for the onset of the Anthropocene should be chosen. Instead, I illustrate how several of the proposed starting dates coincide with or had important zoogeomorphic ramifications. In doing so, readers will gain a sense of how zoogeomorphic processes and patterns have been dramatically altered throughout the late Pleistocene and Holocene by human action.

## 3. Late Pleistocene/early Holocene megafaunal extinctions and the zoogeomorphic implications

The earliest proposed onset of the Anthropocene was tied to megafaunal extinctions associated at least in part with human-induced overkill in the general period 14,000–10,500 BP (Braje and Erlandson, 2013;



**Fig. 1.** Conceptual diagram of the geomorphic activities undertaken by animal species. Diagram is modified from Butler (2006).

Barnosky et al., 2014), with Doughty et al. (2010) specifying a time frame around 13,800 BP specifically tied to the extinction of mammoths in the Siberia-Yukon-Alaska region. Braje and Erlandson (2013, p. 15) noted that 72% of the large mammal genera of central North America went extinct in this timeframe, ‘including mammoths, mastodons, giant ground sloths, horses, tapirs, camels, bears, saber-tooth cats, and a variety of other animals’; and in South America an even larger percentage (83%) of megafauna genera went extinct in the same general period. Cold-adapted megafauna, including mammoths, in northern Eurasia, Siberia, Alaska, and the Yukon went extinct between 14,000 and 11,500 BP (Doughty et al., 2010; Braje and Erlandson, 2013; Lewis and Maslin, 2015).

From a zoogeomorphic perspective, the Pleistocene/Holocene megafaunal extinctions were noteworthy for removing geomorphic impacts similar to those of modern large animals such as elephants, camels, and horses. Haynes (2006, 2012) described how the paleogeomorphic effects of mammoths and mastodons were likely very similar to those created by modern elephants, including trampling and trail creation, digging with tusks, vegetation uprooting, and rubbing and polishing of rock surfaces. His Fig. 8 (Haynes, 2012, p. 104) illustrating mammoth footprints and associated trampling around the muddy edge of a pond is quite similar to modern elephant prints and pond-trampling observed by this author in Kruger National Park, South Africa (Fig. 2). Imagine a scenario where such trampling sites and trail networks were common at specific sites across northern North America and Eurasia. Pleistocene/Holocene-transition camel, horse, and bear impacts were quite probably similar to those of their modern counterparts as well. If humans were indeed a part of the reason for the megafaunal extinctions at the Pleistocene-Holocene transition, as is widely discussed in the literature (e.g., Doughty et al., 2010; Braje and Erlandson, 2013; Smith and Zeder, 2013), such extinctions were the first major human-induced zoogeomorphic alterations to the landscape of the Anthropocene.

#### 4. Early Holocene domestication of plants and animals and associated zoogeomorphic implications

By the early Holocene, in a time frame overlapping somewhat with that of the Pleistocene megafauna extinctions, ‘domestication of plants and animals was underway in several regions including Southwest

Asia, Southeast Asia, New Guinea, and parts of the Americas’ (Braje and Erlandson, 2013, p. 20). The advent and acceleration of agriculture created environmental changes that have led numerous scholars to invoke this broad time period (ranging from as early as 11,000 to 8000–5000 BP) as the beginning of the Anthropocene (as discussed by Steffan et al., 2011; Smith and Zeder, 2013; Lewis and Maslin, 2015; Waters et al., 2016). The deforestation that occurred in favor of agricultural fields and livestock domestication led to increases in atmospheric carbon dioxide (from loss of forest cover) and methane (from livestock emissions) that are cited as a potential marker for the Anthropocene onset (Smith and Zeder, 2013; Waters et al., 2016).

From the zoogeomorphic perspective, livestock grazing by hooved domesticated animals (including, but not limited to, cattle, sheep, goats, yaks, camels, llamas, burros, and horses) has numerous geomorphic ramifications (Fig. 1). As noted by Butler (2013, p. 71), impacts include ‘soil compaction leading to accelerated runoff, gullying that results from accelerated runoff, trail incision, disruption of protective cryptogamic soil crusts in arid areas prone to subsequent aeolian soil erosion, streambank sloughing and resultant channel widening, reduction in the resistance of channel beds resulting from trampling associated with overgrazing..., degradation of stream riffles by the breakdown of the armoring gravels resulting from hoof impacts, and terracette creation’. Grazing and trampling in arid environments accelerates the loss of silt as well as total elemental soil by aeolian erosion, leaving behind distinctly coarser sandy soils (Fig. 3) (Neff et al., 2005). Because of domesticated grazing, sediment fluxes increased in many fluvial systems and resulted in recognizable sedimentary deposits from soil erosion (Waters et al., 2016) that date to this period. Nonetheless, human civilizations with appreciable environmental impact during this time frame were largely restricted to parts of China, Egypt, the Indus Valley, and the Fertile Crescent (Certini and Scalenghe, 2011), with only modest and patchy impacts. The overall zoogeomorphic impacts associated with this period were, then, spatially limited and of only minor consequence on a global scale.

#### 5. Civilization alterations around 2000 BP

By around 2000 BP, widespread civilizations such as the Roman Empire in the circum-Mediterranean region and others elsewhere in



**Fig. 2.** Modern African elephant footprints with a 50-mm lens cap (A), elephant wallow sites (B, C), and elephant trail leading to wallow site (D), all morphologically similar to features attributed to woolly mammoths by Haynes (2006, 2012). All photos taken in Kruger National Park, South Africa, March 2010.



**Fig. 3.** Trampling features in coarse sandy desert in Kuwait created by domesticated camels. (A) Closeup of camel hoof print, scale is in centimeters (upper) and inches (lower). Note coarseness of surrounding sediment; (B) area heavily trampled by domesticated camels, pocket penetrometer in lower part of photograph ca. 10 cm long. Photos courtesy of Faisal Anzah, taken August 2017.

Asia and the Americas had produced much broader, long-lasting impacts on landscapes via deforestation, agricultural plowing and terracing, and grazing (Certini and Scallenghe, 2011). These impacts are visible in a variety of dated anthropogenic soil horizons that Certini and Scallenghe (2011) claimed comprise *Golden Spikes* indicative of the start of the Anthropocene. Some of these soil horizons produced by anthropogenic landscape alterations were attributable to accelerated runoff associated with animal overgrazing and compaction in addition to agriculture and deforestation (Certini and Scallenghe, 2011). Unfortunately, little research has been carried out to identify the zoogeomorphic contribution to the anthropogenic soil horizons dating to this period, and little can be said about zoogeomorphic landscape alterations beyond noting that the impacts of grazing and trampling (see Fig. 1) were becoming more widespread and possibly more intense.

## 6. The Columbian Exchange and resulting zoogeomorphic impacts

A more widely discussed alternative for the onset of the Anthropocene is associated with the so-called *Columbian Exchange*, described by Lewis and Maslin (2015, p. 134) as 'the global transfer of crops, domesticated animals, diseases and human commensals between the Old and New Worlds following the arrival of Europeans in the Americas after 1492 and subsequently developed global circuits of trade'. Species exchanges between the Old World and New World reached an 'irreversible cross-continental movement of species' (Lewis and Maslin, 2015, p. 134) by the year CE 1610, the year of a carbon dioxide minima in the Law Dome ice core dubbed the Orbis Spike by Lewis and Maslin (2015). The dip in global atmospheric carbon dioxide was attributed to the deaths of up to 50 million humans in the New World following European contact, primarily a result of the introduction of smallpox (Lewis and Maslin, 2015); this decline in the human population of the New World reduced the amount of agriculture in the region, allowing for forest regrowth and the sequestering of CO<sub>2</sub>.

### 6.1. Introduction of domesticated megafauna into North and South America

Another important date in the general period of the Columbian Exchange, and one with a significant zoogeomorphic implication, is the year CE 1540, recognized by Barnosky et al. (2014) as the start of the Saintaugustinean North American Land Mammal Age (NALMA). The Saintaugustinean NALMA was defined by those authors on the basis of the introduction of domesticated megafauna, and specifically the modern horse (*Equus caballus*), north of 25°N about 400 years ago. In addition to the modern horse, first appearances in the New World in this period included domesticated cows, sheep, goats, and pigs, as well as domesticated cats and introduced Norway rats and house mice (Barnosky et al., 2014). The Saintaugustinean NALMA is named after Saint Augustine, Florida, USA, where Spanish colonizers established a settlement in 1565. Barnosky et al. (2014) regarded the year CE 1540 as the start of the Saintaugustinean NALMA, however, because of the introduction of horses and other domesticated livestock into northern Mexico and what are now the U.S. states of New Mexico and Arizona by the Coronado expedition that year (horses and other livestock had also quickly been introduced by this time into South America by the Spanish).

The introduction of the domesticated livestock mentioned above had profound zoogeomorphic implications for the New World (North and South America) because of the geographic spread of grazing and trampling by cattle, sheep, and horses with their associated effects on soil infiltration, surface runoff, and initiation of gully erosion (Butler, 2013) (although the role of domesticated livestock, especially cattle, in initiating gully erosion and expansion is a complex and controversial topic (Aby, 2017; Miller, 2017)). These domesticates also displaced native species with significant zoogeomorphic impacts, particularly North American bison (*Bison bison*) and prairie dogs (*Cynomys* sp.). Those impacts, and their abrupt cessation associated with the near-extirpation of bison and the drastic reduction in number of prairie dogs, have been discussed in this journal previously (Butler, 2006).

### 6.2. Beaver trapping in North America

Another major zoogeomorphic impact resulting from European contact was the dramatic reduction in the population of native North American beaver (*Castor canadensis*) caused by trapping. From a pre-contact estimate of as many as 400 million beaver in North America, trapping progressed from eastern Canada and the U.S. in the early seventeenth century across the continent to the west, so that by the mid-nineteenth century the population had been reduced to 6–12 million (Butler and Malanson, 2005; Wohl et al., 2017).

The effects of this drastic reduction in native North American beaver have been discussed in several papers. Butler and Malanson (2005)

presented estimates of the quantity of sediment stored in beaver ponds pre-contact vs. present-day conditions. They showed that between 3 (lowest end of estimated range) and 125 (highest end of estimated range) billion m<sup>3</sup> of sediment would have been sequestered in beaver ponds in North America prior to contact. That range contrasted with only ~1–3.85 billion m<sup>3</sup> of sediment sequestered in modern beaver ponds across the continent.

In wide valley bottoms, beavers with their attendant dams and ponds (Fig. 4) create multithread streams that are stable, reduce downstream erosion by reducing stream velocity, and enhance lateral hydrologic connectivity (Butler, 1995; Burchsted et al., 2010; Polvi and Wohl, 2012; Westbrook et al., 2013; Wegener et al., 2017). Removal of beavers from stream systems across the continent led to 'decreased retention of water, solutes, sediment, and particulate organic matter within river corridors' (Wohl et al., 2017, p. 32). Several authors have commented on how the removal of beavers led to beaver dam failures along stream channels, leading to dam-free channels where subsequent deep entrenchment became common (Marston, 1994; Butler and Malanson, 2005; Pollock et al., 2007; Green and Westbrook, 2009). Removal of beavers led to a shift from clear-flowing streams reported by early colonial settlers to turbid, sediment-laden flow (Butler et al., 2017).

### 6.3. Introduction of exotic species and the resulting zoogeomorphic ramifications

Domesticated livestock described in Section 6.1 were not the only animals introduced as a result of the Columbian Exchange and additional exchanges with far-flung outposts such as Australia and islands across the Pacific Ocean. Introduction of exotic species led to the extinction of numerous native species in North America and on Pacific islands (Braje and Erlandson, 2013; Barnosky et al., 2014), some of which undoubtedly had geomorphic impacts of some importance. Unfortunately, those species were never studied for zoogeomorphic impacts prior to their extinction.

The introduced species, in several cases, have had widespread geomorphic impacts because the absence of natural enemies allowed exotic populations to quickly become established in large numbers. The introduction of rabbits into Australia is all too well known (see Butler et al., 2017, for a recent discussion). Less well known, but with large geomorphic impacts, has been the introduction of burrowing rodents to sub-Antarctic islands where no natural predators existed. Eriksson and Eldridge (2014) illustrated how burrowing house mice (*Mus musculus*) on sub-Antarctic Marion Island have dug extensive burrow systems in solifluction risers, in the process excavating an average of over 8 t of sediment/ha. The burrow systems act as conduits for water and warmer air, leading to 'substantial deleterious and geomorphic

effects on sub-Antarctic ecosystems through their burrowing' (Eriksson and Eldridge, 2014, p. 61), including sediment accumulation, downslope movement of that sediment, and enhanced runoff. Eriksson and Eldridge (2014) also noted that with the exception of two small islands in the Kerguelen group, no significant efforts have been made in the sub-Antarctic to remove mice from islands, suggesting the potential for widespread geomorphic influences and ecosystem damage throughout the region.

In addition to the introduction of exotic animals with lasting zoogeomorphic impacts, we should note that the introduction of exotic flora can also have lasting effects upon the local zoogeomorphic agents. Conceptually, these influences could include the reduction of the range/intensity of zoogeomorphic agents because of introduced exotic plants; the expansion or reduction of population densities of zoogeomorphic animals through feedbacks with the new plant(s); and the reduction of the importance of zoogeomorphic agents by exotic plants stabilizing slopes, soil, and stream banks and floors. These kinds of interactions are beyond the scope of this paper but definitely offer room for future research.

## 7. The Industrial Revolution and zoogeomorphology

Many scientists have advocated the onset or the acceleration of the Industrial Revolution as the starting point for the Anthropocene. The precise starting year (CE 1750 marking the beginning of the Industrial Revolution, CE 1800 marking the widespread establishment across Europe and into North America; see discussion in Steffan et al., 2011; and Smith and Zeder, 2013) is, however, subject to debate. From the perspective of zoogeomorphology, what is more important is how transportation technology (steamships, railroads) and mechanical advances associated with the Industrial Revolution (repeating rifles, barbed wire) accelerated the ability of humans to spread exotic species around the globe and also to nearly exterminate others (bison, prairie dogs). The railroad in particular allowed rapid access into the heartland of North America where the bison herds resided. Although begun soon after the initiation of the Columbian Exchange, the decimation of the bison herds (from an estimated 30–60 million bison at contact to only ~1000 surviving individuals in the 1880s; Butler, 2006) primarily occurred between ca. 1865 and 1880 after construction of the first transcontinental railroad, in concert with fencing of the range and the development of the repeating rifle. Within fewer than two decades, the dramatic geomorphic effects of bison (especially wallowing, trampling, and grazing) were virtually removed from the North American landscape, replaced by grazing cattle whose geomorphic impacts differed from the native bison. Removal of the bison also led to widespread destruction of prairie dog habitat, such that modern-day prairie dogs and their important geomorphic impacts occupy only ca. 1.5% of the area that they occupied prior to contact (Butler, 2006).

The increased speed of transportation offered by the Industrial Revolution also accelerated the spread of exotic/introduced species, including domesticated animals that in many cases subsequently became feral across the landscape. Readers interested in the zoogeomorphic implications of many of these feral animals are referred to previous works by Butler (2006, 2013); the work of Saunders et al. (2013) who specifically addressed the geomorphic impacts of feral rabbits; and recent works examining the geomorphic impacts of feral hogs (Siemann et al., 2009; Hancock et al., 2017). An excellent general overview of the geomorphic impacts of introduced species can be found in Fei et al. (2014).

## 8. The mid-twentieth century as the start of the Anthropocene

The Anthropocene Working Group (Zalasiewicz et al., 2017) has recommended the mid-twentieth century, and specifically the year 1950, as the starting point for the Anthropocene, with radionuclide fallout initiated in 1945 and accelerated in the years following providing what they consider a stratigraphic Golden Spike for the onset. The speed



**Fig. 4.** Multithread stream with numerous beaver ponds and dams in upper center of photo. Photo taken in headwaters of Red Eagle Creek, Glacier National Park, MT, USA, 9 August 1995.

with which changes have occurred since then have led the period beginning in 1950 to be labelled 'The Great Acceleration' (Gillings and Paulsen, 2014). Some have advocated the year 1964, which marked the year of peak radionuclide fallout (the so-called *Bomb Spike*), as a better date for the Anthropocene onset (Lewis and Maslin, 2015; and as discussed in Waters et al., 2016).

Regardless of which specific year might be identified as a mid-twentieth century Anthropocene onset (and from a zoogeomorphic perspective, the discussion is really not germane), a host of zoogeomorphic impacts have occurred during the period since ca. 1950 as a result of human actions. These actions include reintroductions/rewildings of zoogeomorphically important species in areas where they had been previously extirpated or drastically reduced in number, introductions as exotic species, human-built urban infrastructure expansions with resulting impacts on habitat of zoogeomorphic species, and the impacts caused by human-induced climate change that had begun in the late 1800s but accelerated in the latter half of the twentieth century.

### 8.1. Reintroductions of beaver in North America and Europe

Two modern species of beavers exist, the Eurasian beaver (*Castor fiber*) and the North American beaver (*Castor canadensis*). Both species were nearly hunted to extinction by the start of the twentieth century, with fewer than 1500 individuals of *Castor fiber* in eight separate populations (Batbold et al., 2016) and a few hundred thousand *Castor canadensis*, largely in Canada, remaining at that time (Baker and Hill, 2003).

Both species of beavers are renowned as zoogeomorphic agents (see Section 6.2 in this paper). *Castor fiber* has been reintroduced/rewilded in Austria, Belgium, Croatia, Czech Republic, Denmark, England, Estonia, Finland, Hungary, Italy, Latvia, Liechtenstein, Lithuania, Montenegro, Netherlands, Poland, Romania, Scotland, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, and Ukraine (Batbold et al., 2016; Butler et al., 2017 in press). As noted by Butler et al. (2017, p. 5), '(t)he number of beavers reintroduced varies, and in most cases has occurred over too little a time period to determine the direction(s) of change on the landscapes their presence may introduce and whether any phase-state shifts may occur, although the typical patterns of dam construction and pond environment establishment and expansion are occurring.' With population estimates of more than 600,000 Eurasian beavers now in Europe (Batbold et al., 2016), the zoogeomorphic changes as a result of Eurasian beaver reestablishment will be reflected in sedimentary deposits and landforms across the region. Most of these changes will date to no earlier than the immediate post-World War II period and in many areas only to the last one-two decades.

In North America, beaver population numbers are estimated to have rebounded to somewhere in the 6–12 million range (Butler, 1995; Baker and Hill, 2003) across the entirety (but obviously not with the same density) of their pre-contact range. Their geomorphic impacts have been described elsewhere (e.g., Butler, 1995; Burchsted et al., 2010; Polvi and Wohl, 2012; Westbrook et al., 2013; Wegener et al., 2017) and need not be repeated here. One noteworthy new addition to the literature examining the rebound of beaver populations and attendant zoogeomorphic impacts is Johnston (2017), who with colleagues examines the recovery and impact of beavers in Voyageurs National Park, Minnesota, USA.

### 8.2. Introduction of North American beaver as an exotic species in South America

In 1946, the Argentine government imported 20 North American beavers into the Tierra del Fuego region of Patagonia in an attempt to bolster the local economy through the introduction of fur-trapping (Westbrook et al., 2017). With no natural enemies in the region, the population expanded rapidly to a current estimate of over 160,000 individuals. The beavers crossed the Strait of Magellan separating Tierra del

Fuego from mainland South America and have spread across southern Patagonia in Chile and Argentina (Westbrook et al., 2017).

Westbrook et al. (2017, p. 183) describe an interesting zoogeomorphic impact of the introduced beavers in Patagonia, from which this description is taken. Although beavers there have used native *Nothofagus* trees to build dams and impound streams at a few sites,

(at) the majority of sites, beavers actively excavated peat and mineral sediment, moved thousands of cubic meters of sediment within their occupied landscapes and used it to build dams. Beavers were also common in fen ecosystems where pond formation inundated and drowned peat forming mosses and sedges, and triggered a massive invasion of exotic plant species.

Although unrelated to the timing of the onset of the Anthropocene cited by Zalasiewicz et al. (2017), certainly in Patagonia the year 1946 could be considered the onset of a zoogeomorphic Anthropocene!

### 8.3. Introduction of exotic animals into European streams

Although the impacts of recovering or introduced beaver populations in the Americas and Eurasia illustrate a profound zoogeomorphic presence in fluvial systems resulting from human interference, those effects are certainly not the only ways in which humans have influenced the zoogeomorphology of stream systems in the time period since World War II. Additional major human-induced zoogeomorphic impacts on stream systems in this period were the introduction of signal crayfish into streams in Europe and Japan and the introduction of nutria into streams in Europe as well as in North America, Africa, and Asia.

The signal crayfish (*Pacifastacus leniusculus*) is a large, aggressive species of crayfish native to western North America. It was introduced into Japan and over 20 countries in Europe since the 1960s (Harvey et al., 2011, 2014). In Britain, it was introduced in 1976, and within a dozen years it had colonized more than 250 streams (Harvey et al., 2011). The potential zoogeomorphic effects of the introduced crayfish in stream reaches, with implications for the larger catchment scale, were succinctly summarized in an effective flowchart by Harvey et al. (2011). That figure noted that the crayfish affected streambank and streambed sediment. Bank sediments are disturbed by the burrowing activity of the crayfish, which increases fine sediment inputs into streams, and can lead to bank failure with additional sediment input into streams. Crayfish movements on the bed of the stream, associated with instantaneous movements (walking, escaping predation) and prolonged movements (burrowing, feeding, fighting), produce an increase in fine (sand, silt, clay) sediment availability, mobilization, and downstream transport (Harvey et al., 2011, their Fig. 3). A subsequent paper by Harvey et al. (2014) used laboratory and field observations to illustrate the real-world significance of the sediment-moving effects of signal crayfish, which produce pulsed sediment suspension and an 'overall increase in turbidity and... influence sediment dynamics at larger spatio-temporal scales' (Harvey et al., 2014, p. 269). The authors further noted that these effects could include morphological change downstream, the aforementioned increased turbidity, and the transport and mobilization of not only sediments but also sediment-associated nutrients and contaminants. They posited that these effects could have negative impacts on flood risk as well as the ecological status of water bodies (Harvey et al., 2014, p. 270). These collective impacts, all a result of human introduction of an exotic zoogeomorphic species, were initiated about the same time as the Bomb Spike of 1964 – another temporal coincidence, but again illustrating how virtually any starting date for the Anthropocene has attendant striking zoogeomorphic impacts.

Nutria, also called coypu (*Myocastor coypus*), are large, semiaquatic rodents somewhat similar in appearance and size to beavers and muskrats. Nutria were introduced for fur and meat into much of Europe beginning in the 1920s and in the United States in the 1930s. They escaped their commercial enclosures and soon spread into wetlands and

streams throughout their introduced range, living in burrows and levees along stream channels and in earthen dams. The nutria burrows act as conduits within stream levees and earthen dams that lead to piping, levee collapse, and subsequent flooding and sediment redistribution (Bayoumi and Meguid, 2011; Viero et al., 2013). Nutria burrows may have up to 2-m-long tunnels leading to burrow compartments, which themselves can be up to 1 m across (Bayoumi and Meguid, 2011). Expanding rapidly after World War II, nutria have proven difficult to eradicate from their introduced ranges and provide another illustration of human-induced zoogeomorphic expanded impacts coinciding with the mid-twentieth century.

#### 8.4. Expansion of human-built structures and impacts on habitat for zoogeomorphic species

Following World War II in many areas around the world, urban expansion and extension of infrastructures such as superhighways accelerated. These expansions and extensions had deleterious and also positive impacts on zoogeomorphic species. Reduction of wildland and expansion of urban structures and pavements removes habitat for zoogeomorphic species that require solitude and large expanses of relatively untouched wildland. Although logical, little work has been done to examine the deleterious effects of urban expansion and human constructions on zoogeomorphic species habitat.

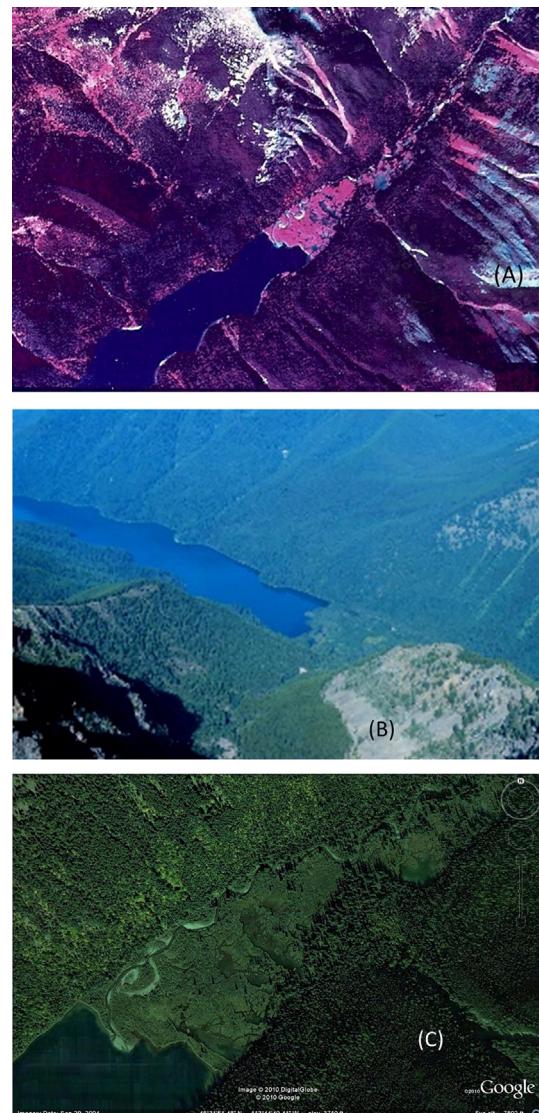
Positive impacts of urban expansion and extension of infrastructure include the creation of potential new habitat for zoogeomorphic species sufficiently able to adapt to new environments. Again, few examples exist in the zoogeomorphic literature, but the effects of construction of new habitat by humans have been studied in the context of mud-nesting swallows. Mud-nesting swallows build nests out of hundreds of individual pellets of mud collected within short distances from nest sites and may use human-built structures in lieu of natural caves and cliff sites (their normal habitat in nonhuman-occupied locations) to support their mud nests (Fig. 6). Martin (1981) described how cave-nesting swallows (*Petrochelidon fulva*) and barn swallows (*Hirundo rustica*) in south-central Texas, USA, expanded their range by constructing mud nests in highway culverts of multiple-passageway concrete construction (the construction of such culverts almost exclusively post-date World War II). Nests were built on culvert walls within about 0.3 m of their ceilings and were constructed of mud and guano pellets in a flared-rim cup shape. A subsequent study by Tsikalas and Butler (2015) described how tens to thousands of such nests were constructed by mud-nesting swallows beneath constructed bridges of Interstate Highway 35 in the central Texas town of San Marcos. Opened in the early 1960s in this area, Interstate Highway 35 provides 15 colony sites for mud-nesting swallows that did not exist prior to the construction of the interstate. In one summer at these sites, swallows transported and used over 500 kg of mud pellets in constructing nests beneath the bridges. The Anthropocene landscape for mud-nesting swallows has expanded dramatically since the mid-twentieth century as a result of human construction and infrastructure expansion.

#### 8.5. Zoogeomorphic impacts of human-induced climate change

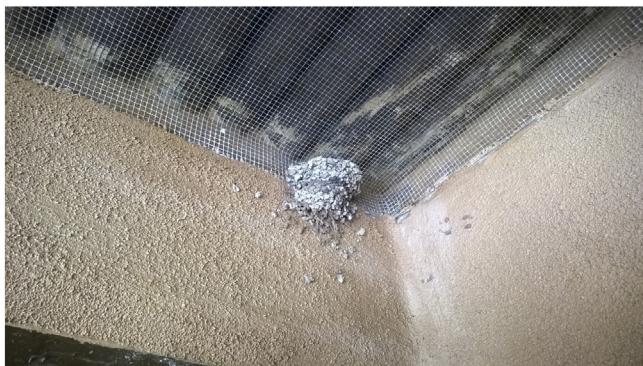
Human-induced climate change, associated with the onset and acceleration of the Industrial Revolution (as discussed in Steffan et al., 2011; Smith and Zeder, 2013; Gillings and Paulsen, 2014), has extended across the nineteenth and twentieth and into the twenty-first centuries. Only recently, however, have scientists examined in any detail the impact of the Great Acceleration on animal populations and distributions, and very few of those studies have considered the zoogeomorphic impacts of climate change. Butler (2012b) described potential climate change impacts on the geographic range and intensity of zoogeomorphic activity of several species including grizzly bears, beavers, and pikas. In a separate paper, Butler (2012a) illustrated how glacial recession caused by human-induced climate change may lead to the extirpation of beaver

populations on mountain deltas in Montana, USA, by removing the source of meltwater that supplies the hyporheic flow feeding long-lived beaver ponds on the low-relief deltas (Fig. 5).

Recently, Beever et al. (2016) described how outlier populations of pika (*Ochotona princeps*), separated from the main geographic distribution of the species in the Sierra Nevada and Rocky Mountains of the American west, have been extirpated since 2011 by climatic warming and negative changes in the local water balances in Zion National Park and Cedar Breaks National Monument in southern Utah, USA. North American pikas live in cool, high alpine terrain in talus slopes and related rock-ice features, especially rock glaciers, boulder streams, and protalus features. Pika species in North America and in Asia are prolific burrowers and maintain extensive excavated dens under the boulder-ice landforms in which they reside (see Butler, 2012b for more detail). They have a high average body temperature (40.1 °C) and a relatively low upper lethal temperature of 43.1 °C and have a high basal metabolic rate making them particularly susceptible to overheating. Pikas burrow



**Fig. 5.** Beaver ponds on the delta at the head of Harrison Lake in Glacier National Park, MT, USA, fed by hyporheic flow from glacial meltwater upstream. Ponds have existed since at least 1984 (A) and are still present in 2017. Note how the beaver ponds are disconnected from the channel of Harrison Creek that flows along the upper portion of the delta in each image. (A) USGS color infrared photo of beaver ponds on Harrison Creek delta, 1984; (B) helicopter view taken 26 July 1994 of Harrison Lake and delta with numerous beaver ponds disconnected from Harrison Creek; (C) Google Earth image (29 September 2004) of Harrison Creek delta replete with beaver ponds and canals, with Harrison Creek flowing along uppermost part of delta apart from the ponds fed by hyporheic flow.



**Fig. 6.** A cup-shaped swallow nest constructed in a covered breezeway connecting adjacent buildings at White Sands National Monument, New Mexico, USA. The lighter-colored mud pellets are comprised of sand particles harvested from the adjacent gypsum sand dunes.

in and underneath the rock surfaces on which they spend their days (Butler, 2012b); and the extirpations in Utah remove the zoogeomorphic imprint of pikas in those areas and are directly attributable to the human-induced changing environmental conditions characterizing the Anthropocene. Other pika distributions in the American west are being monitored (Beever et al., 2016), and other species of pika worldwide are also under considerable threat from warming climates.

## 9. Conclusions

This paper does not take a position on when the Anthropocene began. As has been shown here, for virtually every proposed Anthropocene starting date, important zoogeomorphic impacts have occurred at that time (Table 1). Many of these impacts should or do show up in sedimentary deposits, such as those that characterize beaver pond sediments produced by twentieth century reintroductions of beavers to their native habitats in North America and Eurasia and beaver ponds in Patagonia created by the exotic introduction of beavers there. Others manifest themselves as new landforms, such as entrenched streams or widespread burrows, resulting from a species removal (beavers, prairie dogs, bison) or introduction (rabbits, mice). Human interference with zoogeomorphically active species has profoundly changed stream systems and riparian landscapes across North America and Europe through species removal (beavers) and introduction (signal crayfish, nutria). Domestication of animals around the world and across time produced its own suite of geomorphic impacts and effects on soils. Human construction has altered the available habitat for zoogeomorphic species, in some cases reducing available habitat but in other cases (mud-nesting swallows) providing new niches to be exploited. Climate change associated with the Industrial Revolution and the Great Acceleration is

currently affecting the zoogeomorphic impacts of animal species around the world via species extirpation and impacts on species ranges; yet in spite of this, little scientific work is being done on examining how Anthropocene climate changes are affecting the zoogeomorphic impacts carried out by animal species. A great deal of work could be done in examining the interactions of zoogeomorphology with the Anthropocene, from pre-history to the present, regardless of the Anthropocene's precise starting point. What is needed is a dedicated cadre of scientists prepared to do so.

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**Table 1**

Timeline of proposed starting dates for the Anthropocene with associated zoogeomorphic events.

Proposed starting date	Associated zoogeomorphic events
Mid-twentieth century (CE 1964 Bomb Spike, CE 1945/1950 Radionuclide Onset/Great Acceleration)	Reintroduction of beaver into North America and Europe; Introduction of beaver into South America; Introduction of signal crayfish and nutria into streams; Impacts of anthropogenic climate change; Impacts of urban expansion and infrastructure construction
CE 1750–1800 (Industrial Revolution)	Decimation of North American bison herds; Reduction of prairie dog extent; Acceleration of dissemination of feral animals
CE 1540 (Columbian Exchange)	Introduction of domesticated megafauna to the New World; Widespread overtrapping of North American beaver; Introduction of exotic species from Old World to New
2000 BP (Extensive civilization alterations)	More widespread Old World animal overgrazing and trampling in addition to agriculture and deforestation
11,000–8000 BP (early Holocene domestication of plants and animals)	Old World animal overgrazing and trampling in addition to agriculture and deforestation, spatially limited on a global scale
14,000–10,500 BP (late Pleistocene/early Holocene megafaunal extinctions)	Megafaunal extinctions associated at least in part with human-induced overkill

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